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SIMULATION OF THE BEAM-BEAM INTERACTION WITH TUNE COMPENSATION

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ABSTRACT

If the beam separation d at the first parasitic collision (PC) is varied while all other parameters remain fixed, the core of the two beams sample different working points due to d-dependence of the beam-beam tune shift produced by the PC. In this note we present a beam-beam simulation for the APIARY 6.3D and APIARY 7.5 designs in which we compensate for this d–dependent tune shift by appropriate changes in the working point. This is done in such a way that the tunes of the particle at the center of each beam remain fixed at the values corresponding to the nominal PC separation. The entire analysis is done for two values of the synchrotron tune of the low-energy beam (LEB), namely $\nu_{s+} = 0.0403$ and $\nu_{s+} = 0.05$. In general, the beam blowup curves are smoother with tune compensation than without, and the performance is slightly better for $\nu_{s+} = 0.05$ than for $\nu_{s+} = 0.0403$.

1. Introduction

Most of the beam-beam simulation studies for PEP-II presented in the CDR[1], in the Design Update[2] (DU) and in previous notes[3–6] have focused on the adequacy of the beam separation d at the first PC. For this reason many of the results have been presented in the form of plots in which the four beam blowup factors σ/σ_0 are plotted against $d/\sigma_{0x,+}$, where $\sigma_{0x,+}$ is the nominal horizontal rms beam size of the LEB at the PC location. In these blowup plots the beam separation, d, is taken as a free parameter that is varied while all other parameters are kept fixed.

In particular, in these plots the "bare lattice" working point of each beam is kept fixed for all values of d. Consequently, due to the fact that the PCs induce a d-dependent beam-beam tune shift, the core of the beams sample different areas of the tune plane as d is varied. Since the working

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point was selected from a tune scan with d fixed at its nominal value, the blowup plots obtained at fixed bare-lattice tunes involve this spurious effect, which we assess in this note.

In addition, for historical reasons that are now irrelevant, all beam-beam simulations so far have been done for a LEB synchrotron tune $\nu_{s+} = 0.0403$. In fact, in the CDR and in the DU the stated RF parameters and the expected momentum compaction factor of the LER are such that the synchrotron tune is, instead, $\nu_{s+} = 0.05$. For this reason, in this note we also present comparisons between beam-beam simulations for these two values of ν_{s+} (the HEB synchrotron tune is held fixed at its nominal value, $\nu_{s-} = 0.052$, which is the value we have always used).

We present simulations for the CDR design APIARY 6.3D and the DU design APIARY 7.5 in which the bare-lattice tunes are adjusted in such a way that the beam center remains in the same place of the tune plane as d is changed away from its nominal value (d= 2.82 mm for APIARY 6.3D or d = 3.498 mm for APIARY 7.5). We call this adjustment "tune compensation." For each of these cases, we carry out the simulation for $\nu_{s+} = 0.0403$ or 0.05. Thus there are altogether 8 cases presented in this note. We conclude the following: (1) Performance is better (*i.e.*, beam blowup is less) for $\nu_{s+} = 0.05$ than for 0.0403 for both designs, although the improvement is more noticeable for APIARY 6.3D than for APIARY 7.5. (2) The beam blowup curves (σ/σ_0 *vs.* $d/\sigma_{0x,+}$) are clearly smoother with tune compensation than without tune compensation for APIARY 6.3D for either value of ν_{s+}. This is not true of APIARY 7.5: the beam blowup curves are qualitatively similar whether or not tune compensation is used. (3) In any case, APIARY 7.5 is clearly favored over APIARY 6.3D on account of the larger value of $d/\sigma_{0x,+}$ at the first PC. In Section 4 we offer a plausible hypothesis for the difference in behavior between the two designs.

2. Definition of tune compensation

In lowest-order approximation, the contribution from *each* PC to the beam-beam parameter of a positron at the center of the LEB is[1,2,6]

$$\xi_{0x,+}^{(\mathrm{PC})}(d) = -\frac{r_0 N_- \beta_{x,+}}{2\pi\gamma_+ d^2}, \qquad \xi_{0y,+}^{(\mathrm{PC})}(d) = +\frac{r_0 N_- \beta_{y,+}}{2\pi\gamma_+ d^2} \tag{1}$$

with corresponding expressions for the central electron in the HEB, obtained from the above by the exchange + ↔ –. Also in lowest order approximation, the actual horizontal tune of the central positron is approximately given by

$$\nu_{x,+}^{\mathrm{ctr}} = \nu_{x,+} + \xi_{0x,+} + 2\,\xi_{0x,+}^{(\mathrm{PC})}(d) \tag{2}$$

where ν_{x+} is the "bare lattice" tune, and $\xi_{0x,+}$ is the beam-beam parameter of the main collision at the IP. The expressions for the remaining three tunes are obtained from the above by the substitutions + ↔ – and/or $x \leftrightarrow y$. The factor of 2 in front of the PC beam-beam parameter accounts for the two PCs experienced by the positron in each turn (one on either side of the IP).

Previous[1] tune scans for APIARY 6.3D, which included the effects from the PCs at the nominal separation ($d = 2.82$ mm) suggest a bare-lattice working point $(\nu_x, \nu_y) = (0.64, 0.57)$ for both beams (the integer parts of the tunes are irrelevant for our present purposes). Tune scans for APIARY 7.5 ($d = 3.498$ mm) also suggest[2] the working point (0.64, 0.57), although these scans are not as fine as those for APIARY 6.3D. From Tables 1 and 2, which contain the nominal values of the parameters for both designs, respectively, we obtain

$$\text{APIARY 6.3D:}\quad \begin{cases} \xi_{0x,+}^{(\mathrm{PC})} = -0.000544, & \xi_{0y,+}^{(\mathrm{PC})} = +0.009097 \\ \xi_{0x,-}^{(\mathrm{PC})} = -0.000234, & \xi_{0y,-}^{(\mathrm{PC})} = +0.002345 \end{cases} \tag{3}$$

and

$$\text{APIARY 7.5:}\quad \begin{cases} \xi_{0x,+}^{(\mathrm{PC})} = -0.000336, & \xi_{0y,+}^{(\mathrm{PC})} = +0.006200 \\ \xi_{0x,-}^{(\mathrm{PC})} = -0.000150, & \xi_{0y,-}^{(\mathrm{PC})} = +0.001553 \end{cases} \tag{4}$$

These values lead, in turn, to the following central-particle tunes:

$$\text{APIARY 6.3D:}\quad \begin{cases} \nu_{x,+}^{\mathrm{ctr}} = 0.668911, & \nu_{y,+}^{\mathrm{ctr}} = 0.618195 \\ \nu_{x,-}^{\mathrm{ctr}} = 0.669529, & \nu_{y,-}^{\mathrm{ctr}} = 0.604691 \end{cases} \tag{5}$$

and

$$\text{APIARY 7.5:}\quad \begin{cases} \nu_{x,+}^{\mathrm{ctr}} = 0.669327, & \nu_{y,+}^{\mathrm{ctr}} = 0.612400 \\ \nu_{x,-}^{\mathrm{ctr}} = 0.669701, & \nu_{y,-}^{\mathrm{ctr}} = 0.603104 \end{cases} \tag{6}$$

Our prescription for tune compensation is, then, the following: when d takes on values different from 2.82 mm for APIARY 6.3D or 3.498 mm for APIARY 7.5, the bare lattice tunes are varied away from (0.64, 0.57) according to Eqs. (1–2) in such a way that the central-particle tunes remain fixed at the values given by Eqs. (5) or (6), respectively.

3. Assumptions

The assumptions used in our beam-beam studies are spelled out in detail elsewhere.[1–7] Here is a summary:

We consider only the linear approximation to the lattice, which is therefore fully described by the tunes, the lattice functions at the IP and PCs, and the intervening phase advances. We imagine the lattice divided up into two symmetrical “short” arcs, from the IP to each of the two PCs, and one “long” arc, from one PC to the other. The lattice functions and phase advances $\Delta\nu$ are listed in Tables 1 and 2. The lattice is tuned by changing the phase advance of the long arc; the phase advances $\Delta\nu$ of the short arcs remain fixed.

The RF wavelength, λ_{RF}, is 0.6298 m, and we consider only the nominal value for the bunch spacing, namely $s_B = 2\lambda_{RF} = 1.2596$ m. Therefore the first PC occurs at a distance Δs = 0.6298 m from the IP.

The nominal beam-beam parameter ξ_0 is 0.03 (all four beam-beam parameters are equal), and the nominal luminosity is $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}. The resultant numbers of particles per bunch, nominal emittances, rms beam sizes and rms angular divergences at the IP are determined by the lattice functions, collision frequency, and the primary parameters ξ_0 and $\mathscr{L}_0$, and are also listed in the tables. The rms bunch length σ_ℓ, rms energy spread σ_E/E and synchrotron tune ν_s are different for the two beams, but are held fixed at their specified values when d is changed.

As mentioned in Section 1, the value of the synchrotron tune of the LEB we have used so far is $\nu_{s+} = 0.0403$. The RF parameters in Tables 1 and 2, particularly peak voltage V_{RF} and momentum compaction factor α, are consistent with this value. However, the value specified in the CDR and DU is, instead, $\nu_{s+} = 0.05$. The corresponding peak voltage is V_{RF} = 9.5 MV and, even though details of the LER lattice remain to be finalized, its momentum compaction factor is expected to be closer to $\alpha = 1.5 \times 10^{-3}$ than to 1.15×10^{-3}, which is the value listed in the tables below. We have carried out simulations for both values of the LEB synchrotron tune. As mentioned in the previous paragraph, we emphasize that, when we change ν_{s+} from 0.0403 to 0.05 in these simulations, we hold fixed the rms bunch lengths, rms energy spreads and damping times.

We use here the simulation code TRS,[7] whose details are explained in Ref. 1. In all cases presented here we have chosen 256 "superparticles" per bunch divided longitudinally into five slices, or bins, in order to represent the thick lens effects during the beam-beam collision. In all cases we have run the simulations for 25,000 turns, or about five damping times. The beam blowup plotted in the figures below is determined by averaging over the last 2,500 turns of the run. The code was run on a Cray-2S/8128 computer at NERSC. Under these conditions (256 superparticles per beam, 5 slices and 25,000 turns), each run takes ~22 CPU min, and the CPU time scales approximately linearly with any of these three variables in this parameter regime.

4. Discussion of results and conclusions

The results of the simulations for APIARY 6.3D are displayed in Fig. 1, which shows the beam blowup factors σ/σ_0 *vs.* the normalized PC separation, $d/\sigma_{0x,+}$. As explained above, in the two top plots ("no tune compensation") we vary d while keeping all other parameters fixed. In the two bottom plots ("with tune compensation") we vary the nominal working points with d as explained in Sec. 2. The nominal value of the PC separation, d =2.82 mm, is indicated by an arrow; it corresponds to $d/\sigma_{0x,+}$=7.57. The two plots on the left have an LEB synchrotron tune ν_{s+} = 0.0403, while those on the right have $\nu_{s+} = 0.05$. As mentioned above, in going from $\nu_{s+} = 0.0403$ to $\nu_{s+} = 0.05$ we have held fixed the bunch lengths, energy spreads and damping times. The top left figure (case 6A) is reproduced from Ref. 3.

Figure 2 shows the corresponding simulation results for the case of APIARY 7.5. The nominal value of the PC separation, d =3.498 mm, is indicated by the arrow, and it corresponds, in this case, to $d/\sigma_{0x,+}$=9.64. The top left figure (case 7A1) is reproduced from Ref. 4.

In the simulations for APIARY 6.3D (Fig. 1) the normalized PC separation $d/\sigma_{0x,+}$ is varied from 4 to 11 (4 to 12 in the case of APIARY 7.5, Fig. 2); the corresponding variation of the working point due to the tune compensation is largest for the vertical tune of the LER, and it amounts to $\delta\nu \approx 0.01$. Variations of this size are well within the tuning range of existing machines such as CESR, even when the beams are in collision.[8]

We summarize our conclusions as follows:

(1) By making "horizontal" comparisons in Figs. 1 and 2, we conclude that performance is better (*i.e.*, beam blowup is less) for ν_{s+} = 0.05 than for 0.0403 for both designs, although the improvement is more noticeable for APIARY 6.3D than for APIARY 7.5. This improvement seems to run counter to one of the ingredients of "transparency symmetry," which requires, among others, the equalities[9]

$$\left(\frac{\sigma_\ell \nu_s}{\beta_x^*}\right)_+ = \left(\frac{\sigma_\ell \nu_s}{\beta_x^*}\right)_- \quad \text{and} \quad \left(\frac{\sigma_\ell \nu_s}{\beta_y^*}\right)_+ = \left(\frac{\sigma_\ell \nu_s}{\beta_y^*}\right)_- \tag{7}$$

In fact, the parameters in Tables 1 or 2 violate these equalities at the ~40% level for ν_{s+} = 0.0403,

$$\begin{aligned} \left(\frac{\sigma_\ell \nu_s}{\beta_x^*}\right)_+ &= 1.07\times 10^{-3}, \qquad \left(\frac{\sigma_\ell \nu_s}{\beta_x^*}\right)_- = 6.93\times 10^{-4} \\ \left(\frac{\sigma_\ell \nu_s}{\beta_y^*}\right)_+ &= 2.69\times 10^{-2}, \qquad \left(\frac{\sigma_\ell \nu_s}{\beta_y^*}\right)_- = 1.73\times 10^{-2} \end{aligned} \tag{8}$$

and at the ~90% level for ν_{s+} = 0.05,

$$\begin{aligned} \left(\frac{\sigma_\ell \nu_s}{\beta_x^*}\right)_+ &= 1.33\times 10^{-3}, \qquad \left(\frac{\sigma_\ell \nu_s}{\beta_x^*}\right)_- = 6.93\times 10^{-4} \\ \left(\frac{\sigma_\ell \nu_s}{\beta_y^*}\right)_+ &= 3.33\times 10^{-2}, \qquad \left(\frac{\sigma_\ell \nu_s}{\beta_y^*}\right)_- = 1.73\times 10^{-2} \end{aligned} \tag{9}$$

It is therefore interesting that performance is improved, albeit slightly, when the violation of the equality is increased. We believe that a more refined tune scan for APIARY 7.5 would reveal a working point slightly away from (0.64, 0.57) which would imply a relative improvement in behavior comparable to that seen in APIARY 6.3D. We also conjecture that, generally speaking, when a “good” working point has been found, such as (0.64, 0.57) for either design, luminosity performance becomes much more sensitive to slight changes in the working point than to relatively large departures from transparency symmetry.

(2) By making “vertical” comparisons in Fig. 1, we see that the beam blowup curves are clearly smoother and flatter with tune compensation than without tune compensation for APIARY 6.3D for either value of ν_{s+}, down to some “threshold” value of $d/\sigma_{0x,+}$ where beam blowup takes off rapidly. This shows that the smoother increase in the blowup curves in the uncompensated case is due to the beam core moving around in tune space. For APIARY 7.5, the curves in Fig. 2 are qualitatively similar whether or not tune compensation is used. Since all tune compensation does is to keep the beam core at a fixed working point as d varies, this observation means that, for APIARY 7.5, the observed blowup is probably caused by a few particles away from the beam center. This means that a better working point can probably be found for APIARY 7.5 quite close to (0.64, 0.57). From these results one can also say that the uncompensated simulations, which have the advantage of being simpler, are reliable, if slightly pessimistic, guides to beam blowup behavior.

(3) In any case, APIARY 7.5 is clearly favored over APIARY 6.3D on account of the larger nominal value of $d/\sigma_{0x,+}$, which provides a larger safety margin for the design parameter d.

5. Acknowledgements

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6. References

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TABLE 1

APIARY 6.3D PRIMARY PARAMETERS

Nominal CDR case; $\mathcal{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)	HER (e^-)
$\mathcal{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}	
C [m]	2199.32	2199.32
E [GeV]	3.1	9.0
s_B [m]	1.2596	1.2596
f_c [MHz]	238.000	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	5.630×10^{10}	3.878×10^{10}
I [A]	2.147	1.479
ε_{0x} [nm-rad]	91.90	45.95
ε_{0y} [nm-rad]	3.676	1.838
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [μm]	185.6	185.6
σ^*_{0y} [μm]	7.426	7.426
τ_x [turns]	5,014	5,014
τ_y [turns]	5,014	5,014

TABLE 1 (contd.)

APIARY 6.3D IP AND PC PARAMETERS

Nominal CDR case; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)		HER (e^-)	
Δs [cm]	62.9816			
d [mm]	2.82			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1643	0	0.1111
$\Delta\nu_y$	0	0.2462	0	0.2424
β_x [m]	0.375	1.51	0.750	1.30
β_y [m]	0.015	25.23	0.030	13.01
α_x	0	–2.42	0	–1.06
α_y	0	–29.25	0	–18.74
σ_{0x} [µm]	185.6	372.4	185.6	244.4
σ_{0y} [µm]	7.426	304.5	7.426	154.6
$\sigma_{0x'}$ [mrad]	0.495	0.646	0.248	0.274
$\sigma_{0y'}$ [mrad]	0.495	0.353	0.248	0.223
d/σ_{0x}	0	7.570	0	11.538
ξ_{0x}	0.03	–0.000544	0.03	–0.000234
ξ_{0y}	0.03	+0.009097	0.03	+0.002345
$\xi_{0x,tot}$ a)	0.0289		0.0295	
$\xi_{0y,tot}$ a)	0.0482		0.0347	

a) The total nominal beam-beam parameter is defined to be $\xi_{0,tot} \equiv \xi_0^{(IP)} + 2\xi_0^{(PC)}$.

TABLE 2

APIARY 7.5 PRIMARY PARAMETERS
Nominal DU case; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)	HER (e^-)
$\mathscr{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}	
C [m]	2199.32	2199.32
E [GeV]	3.1	9.0
s_B [m]	1.2596	1.2596
f_c [MHz]	238.000	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	5.630×10^{10}	3.878×10^{10}
I [A]	2.147	1.479
ε_{0x} [nm-rad]	91.90	45.95
ε_{0y} [nm-rad]	3.676	1.838
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [μm]	185.6	185.6
σ^*_{0y} [μm]	7.426	7.426
τ_x [turns]	5,014	5,014
τ_y [turns]	5,014	5,014

TABLE 2 (contd.)

APIARY 7.5 IP AND PC PARAMETERS
Nominal DU case; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; $\xi_0 = 0.03$

	LER (e^+)		HER (e^-)	
Δs [cm]	62.9816			
d [mm]	3.498			
	IP	1st PC	IP	1st PC
$\Delta \nu_x$	0	0.1645	0	0.1112
$\Delta \nu_y$	0	0.2462	0	0.2424
β_x [m]	0.375	1.433	0.750	1.279
β_y [m]	0.015	26.46	0.030	13.25
α_x	0	–1.680	0	–0.840
α_y	0	–41.988	0	–20.994
σ_{0x} [μm]	185.6	362.9	185.6	242.4
σ_{0y} [μm]	7.426	311.9	7.426	156.1
$\sigma_{0x'}$ [mrad]	0.495	0.495	0.248	0.248
$\sigma_{0y'}$ [mrad]	0.495	0.495	0.248	0.248
d/σ_{0x}	0	9.639	0	14.429
ξ_{0x}	0.03	–0.000336	0.03	–0.000150
ξ_{0y}	0.03	+0.006200	0.03	+0.001553
$\xi_{0x,tot}$ a)	0.0293		0.0297	
$\xi_{0y,tot}$ a)	0.0424		0.0331	

a) The total nominal beam-beam parameter is defined to be $\xi_{0,tot} \equiv \xi_0^{(IP)} + 2\xi_0^{(PC)}$.